GaAs SCHOTTKY BARRIER DIODES FOR THZ APPLICATIONS

BB-2

Thomas W. Crowe, William C.B. Peatman, Perry A.D. Wood and Xiaolei Liu

Semiconductor Device Laboratory
University of Virginia
Charlottesville, Virginia 22903

ABSTRACT

GaAs Schottky barrier diodes are used as nonlinear elements for a variety of scientific applications at frequencies as high as 3 THz. The factors that limit the high frequency performance of these diodes are reviewed and the design process is discussed. Recent results with ultra-small Schottky anodes are presented and conclusions are draw about the future of Schottky diodes at THz frequencies.

I. INTRODUCTION

Heterodyne receivers based on GaAs Schottky diodes have been developed for applications in the frequency range from 100 GHz to over 3 THz. These receivers have high sensitivity, large spectral resolution ($\nu / \Delta\nu > 10^6$) and large instantaneous bandwidth (> 1 GHz), and are used for a variety of scientific applications including radio astronomy [1,2,3], studies of the upper atmosphere [4], chemical spectroscopy [5] and plasma diagnostics [6]. For applications that require the maximum possible sensitivity, superconductor-insulator-superconductor (SIS) devices are replacing Schottky diodes at frequencies below 600 GHz [7,8]. However, it is not clear when, or if, the SIS devices will be extended to THz frequencies. Also, the need for liquid helium cooling of SIS devices will present severe problems for long duration space applications such as investigations of the atmosphere. Thus, it appears that the Schottky devices will continue to play a critical role at THz frequencies for the foreseeable future.

Over the last several years the performance of Schottky heterodyne receivers has continued to improve, as is described in a number of recent publications [1,9,10 for example]. In the following sections, we will review the basic operation of Schottky mixer elements, consider the factors that limit the high frequency performance of these devices, discuss the design process that has been used to achieve the best receiver performance, and describe some recent experimental results.

II. SCHOTTKY MIXER ELEMENTS

A scanning electron micrograph of a whisker contacted Schottky diode chip, a schematic diagram of the chip structure and a simple equivalent circuit are shown in Fig. 1. Although planar (integrated) Schottky diodes are now available [11,12], the whisker contact to a "honeycomb" anode array yields the minimum shunt capacitance [13], a requirement for THz frequency applications. The nonlinear resistance of the metal-semiconductor junction, R_j, is used for mixing applications. The I-V curve for the diode junction is exponential, and, in principle, the conversion efficiency of the junction can approach the theoretical limit for an ideal resistive mixer. However, the diode series resistance and junction capacitance degrade the receiver performance by preventing a fraction of the signal power from being coupled to the nonlinear resistance. The series resistance primarily consists of the resistance of the undepleted epitaxial layer and the heavily doped substrate. (The ohmic contact typically adds negligible resistance.) The junction capacitance is due to charge storage in the depletion region.

The equivalent circuit also includes noise sources associated with the resistive elements. These noise sources limit the sensitivity of the receiver. The noise of the junction is described as shot-noise, while the series resistance is generally assumed to generate thermal noise. However, it is important to consider that at high frequencies the current density can be quite large, leading to a non-equilibrium electron distribution in the series resistance, and increased noise.

A primary goal of the diode design process is to minimize the series resistance and junction capacitance so that the maximum possible signal power is coupled to the nonlinear resistance. However, these two circuit elements are linked through the physical design of the diode. For example, reducing the anode diameter and decreasing the doping density of the epitaxial layer yield lower values of junction capacitance, but at the cost of increased series resistance. It has been shown that by <u>increasing</u> the epitaxial doping density and <u>reducing</u> the anode diameter, the series resistance - junction capacitance product can be reduced [14,10]. This has led to the development of the most successful THz frequency diodes. However, this also leads to reduced ideality of the diode I-V curve and increased shot-noise. The design of optimized diodes is further complicated by the requirement to impedance match the diode to the mixer circuit at the signal frequency and the trade-offs between shot and thermal noise sources [15].

III. LIMITATIONS TO THE THZ PERFORMANCE OF SCHOTTKY DIODES

<u>Millimeter Wavelength Schottky Diodes</u>

It is perhaps easiest to understand the limitations of Schottky diodes at THz frequencies by first considering their performance at lower frequencies. The design parameters of a successful 100 GHz diode and its performance in a heterodyne receiver are shown in Table I. At this relatively low frequency the junction capacitance need not be so small, and thus relatively large anodes can be used on low doped epitaxial layers. Because of the low doping density, the diodes have substantially increased nonlinearity at cryogenic temperatures, and therefore reduced shot-noise. In addition, at this frequency the diode can be biased so that the current density is low enough that electron heating effects are negligible, and the mixer performance is truly shot-noise-limited [16,17]. Thus, at 100 GHz the diode performance is quite well understood, and the noise temperature of the receiver is adequately described by conventional mixer analysis techniques [18].

<u>Long Submillimeter Wavelength Schottky Diodes (300-650 GHz)</u>

The design parameters of diodes that have given state-of-the-art performance between 300 and 650 GHz are also shown in Table I. As the frequency is increased, the design of the diode becomes more complicated, primarily due to the increased shunting effect of the junction capacitance. To alleviate this problem, we reduce the anode diameter to maintain a nearly constant value of ωC_j. Since we also want to maintain the same series resistance, we must reduce the $R_s C_{jo}$ product by increasing the epitaxial layer doping density. Although it might seem that maintaining a constant $\omega R_s C_{jo}$ product will allow us to maintain a constant receiver noise temperature with frequency, this is not the case for two primary reasons. First, the increased doping density increases the shot-noise, so that the mixer noise temperature should increase proportionately with frequency [15]. Second, by reducing the junction capacitance proportionately with frequency we are not able to maintain the same signal coupling to the junction as is achieved at lower frequencies. This is because

BB

CH3141-9/92/0000-1141$01.00 © 1992 IEEE

both R_j and X_j ($1/\omega C_j$) are inversely proportional to area, so that the shunting effect of the capacitance cannot be reduced by changing the area. The main benefit of reducing the anode diameter as frequency increases is to maintain a good impedance match between the diode and the mixer circuit.

The data in Table I clearly indicates the trend toward higher doping densities and smaller anode diameters, and the steady increase in receiver noise temperature with frequency.

Schottky Diodes at THz Frequencies

As the frequency is increased toward 1 THz, several additional effects further degrade the diode performance. One of the most important is the increase in the series resistance of a given diode with frequency [19]. A primary cause of this is the skin effect, which constrains the current to flow along the edge of the chip substrate. Although this effect will add several ohms even at 100 GHz [18], it becomes much more important at THz frequencies. Also, at THz frequencies the inertia of the electrons adds an inductive element to the circuit model and dielectric relaxation adds a capacitive element. At the plasma resonance frequency the inertial and dielectric effects resonate, causing a large increase in series resistance [20]. To avoid this problem the doping density of both the epitaxial layer and substrate should be high enough so that plasma resonance is not a limiting factor [21,22].

A second effect that becomes increasingly important as the frequency approaches 1 THz was recently discovered by Kollberg et al. [23]. In their investigation of high frequency GaAs varactor diodes, they found that standard varactor circuit simulators were assuming that the electron velocity in the GaAs crystal was capable of greatly exceeding the electron saturation velocity. When velocity saturation effects were included in the simulations, the predicted varactor performance was much worse and more consistent with experimental data.

It is probable that velocity saturation effects will explain why submillimeter wavelength mixers never perform as well as predicted by computer analyses. To understand this, we can consider the motion of electrons in the epitaxial layer during a local oscillator (LO) cycle. At the forward peak of the LO voltage waveform the epitaxial layer is completely undepleted and electrons are readily flowing over the Schottky barrier. At the reverse peak of the cycle a significant layer of the semiconductor material under the anode is depleted and the junction is nearly an open circuit. It is the switching from a state where electrons readily flow over the barrier to the open circuit state that allows mixing to occur. However, as the frequency increases the electrons must deplete and undeplete the epitaxial layer more quickly. At some point the maximum velocity of the electrons is reached, and the electrons can no longer follow the LO voltage. The result is a decrease in the modulation of the depletion layer depth and therefore a reduced nonlinearity of the diode, which degrades mixing performance. Furthermore, when the fields in the semiconductor are large enough to cause velocity saturation, intervalley scattering will occur. This should result in a significant increase in the amount of noise generated in the series resistance.

We are using a standard mixer circuit analysis program [18,24] to investigate velocity saturation effects in GaAs mixer diodes. When these effects are neglected, the program assumes that the electrons in the GaAs epitaxial layer have a constant mobility and the assumed current density is allowed to increase without bound as the frequency and LO power level are increased. This leads to very optimistic predictions of mixer performance, which are as much as a factor of five better than our experimental measurements even at 585 GHz. The results from an upgraded mixer analysis, which uses a field dependent mobility and includes intervalley scattering noise, will be presented at the symposium.

IV. THE DESIGN OF GaAs SCHOTTKY DIODES FOR THZ FREQUENCIES

Over the last several years, our laboratory has designed and fabricated Schottky diodes with improved performance at THz frequencies [14,10]. This has been achieved by increasing the epitaxial layer doping density and decreasing the anode diameter to maintain a dc measured series resistance between 10 and 30 Ω. This has led to steady increases in the diode's figure-of-merit cut-off frequency, defined as $\nu_{co} = 1/(2\pi R_s C_{jo})$. The main difficulty with this strategy has been the requirement for ever smaller dimensions.

The thickness of the epitaxial layer is also an important design parameter. We have chosen to maintain the layer thickness, t_{epi}, equal to a zero-bias depletion depth, X_{do}, i.e.

$$t_{epi} = X_{do} = \sqrt{\frac{2\varepsilon}{qN_d} V_{bi}} \tag{1}$$

where N_d is the epitaxial layer doping density and V_{bi} is the built-in potential of the Schottky barrier. Thus, as we have increased the doping density we have also reduced the thickness of the epitaxial layer. We feel that any additional epitaxial material simply adds series resistance without benefit. Although we acknowledge that an even shorter layer may yield slightly improved performance, this has not yet been demonstrated. Also, as doping density is increased the layers are becoming exceedingly thin already.

The justifications for these design rules are quite simplistic. First, we would like to ensure that the diodes are reasonably well matched to the RF circuit. This means that the capacitance must be decreased with frequency and a series resistance in the 10-30 Ω range is reasonable. Second, we ensure that high frequency effects such as skin effect and plasma resonance do not raise the series impedance beyond acceptable values. A finite difference technique has been used to determine the field distribution in the GaAs chip and calculate the series impedance [21,22]. This analysis, which incorporates carrier inertia and dielectric relaxation, has yielded the following conclusions:

1) To reduce spreading resistance and eliminate plasma resonance in the substrate, its doping density should be as large as possible.

2) The doping density of the epitaxial layer should be high enough that the plasma resonance frequency is well above the intended operating frequency. A doping density as high as $1\text{x}10^{18}$ cm^{-3} is proposed for 1 THz, and $5\text{x}10^{18}$ cm^{-3} for 5 THz.

3) The optimum anode diameter, based on obtaining the minimum $R_s C_{jo}$ product and a reasonable impedance level, was shown to be quite small. Anode diameters of 0.5 µm at 1 THz and 0.15 µm at 5 THz were proposed.

A third justification for these design rules is that the increased doping density reduces the distance the electrons are required to move in order to switch the diode between the conducting and non-conducting states. This can be seen by expressing the depletion depth as a function of applied voltage, V_a, and inverting this expression to the form

$$(V_{bi} - V_a) = \frac{qN_d}{2\varepsilon} X_d^2 \; . \tag{2}$$

The value $V_{bi} - V_a$ is the potential difference from the conduction band in the undepleted portion of the epitaxial layer to the top of the barrier. The greater this value, the less current flows over the barrier. For larger values of N_d a smaller increase in X_d is needed to turn off the current, thus the electrons need not be moved so far from the metal-semiconductor interface. Since the electrons must travel at some finite velocity, it is clear that a shorter required distance means a greater frequency response. In light of the recent discovery of velocity saturation effects, it is clear that this design rule is even more important than previously suspected.

V. RECENT EXPERIMENTAL RESULTS

Table I shows receiver noise temperatures that have been reported by a variety of researchers over the frequency range from 100 GHz through 2.5 THz. These results were chosen to represent the current state-of-the-art in Schottky receivers. For consistency, all values have been converted to single-sideband receiver noise temperatures by assuming that $T_{rec}^{SSB} = 2T_{rec}^{DSB}$ when double-sideband values were quoted. The trend toward higher doping density and smaller anode diameters is clear, as is the increase in noise temperature with frequency. Noise temperature is also expressed in units of hv/k, which is common when considering the quantum limited noise of SIS devices. These values show that the noise temperature is increasing much more rapidly than the frequency.

Figure 2 is a scanning electron micrograph of our most recent GaAs Schottky diode chip. The quarter micron diameter anodes were defined by electron beam lithography and reactive ion etching at the National Nanofabrication Facility at Cornell University. The fabrication process and initial diode evaluation are reported in another publication [25]. These are the smallest high quality, lithographically defined diodes yet fabricated. The measured zero-bias junction capacitance of 0.25 fF and series resistance of 25 Ω yield a figure-of-merit cut-off frequency of 25 THz. Based on our previous results, these diodes should yield record performance in the frequency range from 1-5 THz. Preliminary measurements have shown that this diode has a record video response of 200 V/W at 2.5 THz. A preliminary heterodyne measurement at 1.4 THz (noted in Table I) indicates record receiver sensitivity. Further high frequency measurements will be presented at the symposium.

VI. CONCLUSION

The performance of heterodyne receivers based on GaAs Schottky barrier diodes continues to improve, and this technology will play a critical role in a variety of scientific applications for the foreseeable future. Much of the improvement in the diodes has been realized through the use of design rules which are based on a simple understanding of diode operation and experimental measurements. The reduction in anode diameter and increased epitaxial layer doping density have led to the realization of diodes with extremely high cut-off frequency and record performance at THz frequencies. The recent fabrication of quarter-micron diameter anodes on heavily doped GaAs should yield additional improvements in THz receiver performance. Further reductions in anode diameter, to the 0.1 μm range, are being pursued for the highest frequencies (> 3 THz).

Although numerical analyses of the complete mixer circuit yield fairly accurate predictions of receiver performance at frequencies in the 100 GHz range, this has not been the case at THz frequencies. This is mainly due to a failure to recognize a major limitation to the high frequency performance of the diodes. Specifically, the analyses have assumed a constant electron mobility, and therefore assume that the electron velocity can be increased without bound. Incorporation of a field dependent mobility and intervalley scattering noise should make these analyses much more accurate. This will greatly accelerate the optimization of diodes for particular operating frequencies.

ACKNOWLEDGEMENT

This work was supported by the National Science Foundation (ECS-9113123) and the U.S. Army.

REFERENCES

[1] Hans-Peter Röser, "Heterodyne Spectroscopy for Submillimeter and Far-Infrared Wavelengths From 100 μm to 500 μm," Infrared Physics, Vol. 32, pp. 385-407, 1991.

[2] J. Zmuidzinas, A.L. Betz and R.T. Boreiko, "A Corner-Reflector Mixer Mount for Far Infrared Wavelengths," Infrared Phys., Vol. 29, No. 1, pp. 119-131, (1989)

[3] A.I. Harris, D.T. Jaffe, J. Stutzki and R. Genzel, "The UCB/MPE Cassegrain Submillimeter Heterodyne Spectrometer," Int. J. IR and MM Waves, Vol. 8, No. 8, pp. 857-883, 1987.

[4] J.W. Waters, "Microwave Limb Sounding of the Earth's Upper Atmosphere," Atmospheric Research, Vol. 23, pp. 391-410, 1989.

[5] K.M. Evenson, D.A. Jennings and F.R. Petersen, "Tunable Far-Infrared Spectroscopy," Appl. Phys. Lett., Vol. 44, No. 6, pp. 576-578, March 1984.

[6] R. Behn, D. Dicken, J. Hackman, S.A. Salito and M.R. Siegrist, "Ion Temperature Measurements of a Tokamak Plasma by Collective Thomson Scattering of D_2O Laser Radiation," LPR 357/88, Oct. 1988.

[7] A.W. Lichtenberger, D.M. Lea, A.C. Hicks, J.D. Prince, R. Densing, D. Peterson, B.S. Deaver, "Nb Based Mixer Elements for Millimeter and Submillimeter Wavelengths," Digest of the Second International Symposium on Space Terahertz Technology, Pasadena, CA, pp. 439-458, Feb. 1991.

[8] J. Zmuidzinas, H.G. LeDuc, "Quasi-Optical Slot Antenna SIS Mixers," to be published in IEEE Trans. Microwave Theory Tech., 1992.

[9] A.L. Betz and R.T. Boreiko, "Far-Infrared Heterodyne Technology," Proceedings of the 29th Liege International Astrophysical Colloquium "From Ground-Based to Space-Borne Submillimeter Astronomy," Liege, Belgium, July, 1990.

[10] T.W. Crowe, R.J. Mattauch, H.P. Roeser, W.L. Bishop, W.C.B. Peatman, "GaAs Schottky Diodes for THz Mixing Application," Invited paper accepted for IEEE Proc., Special Issue on Terahertz Technology, to appear in 1992.

[11] W.L. Bishop, K. McKinney, R.J. Mattauch, T.W. Crowe and G. Green, "A Novel Whiskerless Schottky Diode for Millimeter and Submillimeter Wave Applications," Proc. 1987 IEEE MTT-S Intl. Symp., Las Vegas, NV, 607-610, June 1987.

[12] W.L. Bishop, T.W. Crowe, R.J. Mattauch, P.H. Ostdiek, W.C.B. Peatman, H. Dossal, B.J. Rizzi, "Planar Diode Technology for Millimeter and Submillimeter Wavelengths," Digest of the First Int. Semiconductor Device Research Symp., Charlottesville, VA, pp. 49-52, Dec. 1991.

[13] D.T. Young and J.C. Irvin, "Millimeter Frequency Conversion Using Au-n-Type GaAs Schottky Barrier Epitaxial Diodes with a Novel Contacting Technique," Proceedings of the IEEE, pp. 2130-2131, Dec. 1965.

[14] W.C.B. Peatman and T.W. Crowe, "Design and Fabrication of 0.5 micron GaAs Schottky Barrier Diodes for Low-Noise Terahertz Receiver Applications," *Int. Journal on Infrared and Millimeter Waves,* Vol. 11, No. 3, 1990, pp. 355-365.

[15] T.W. Crowe, P.A.D. Wood, W.C.B. Peatman and B.J. Rizzi, "GaAs Schottky Diodes for Mixing Applications Beyond 1 THz," Conf. Digest 16th Int'l Conf. IR and MM Waves, Lausanne, pp. 468-469, August 1991.

[16] C.R. Predmore, A.R. Räisänen, N.R. Erickson, P.F. Goldsmith and J.L.R. Marrero, "A Broad-Band, Ultra-Low-Noise Schottky Diode Mixer Receiver for 80 to 115 GHz," IEEE Trans. Microwave Theory Tech., Vol. MTT-32, pp. 498-506, May 1984.

[17] N.R. Erickson, P.F. Goldsmith, G. Novak, R.M. Grosslein, P.J. Viscuso, R.B. Ercikson and C.R. Predmore, "A 15-Element Focal Plane Array for 100 GHz," IEEE Trans. Microwave Theory Tech., Vol. MTT-40, No. 1, pp. 1-11, Jan. 1992.

[18] D.N. Held and A.R. Kerr, "Conversion Loss and Noise of Microwave and Millimeter-Wave Mixers: Part 1 - Theory and Part 2 - Experiment," IEEE Trans. Microwave Theory Tech., Vol. MTT-26, No. 2, pp. 49-61, Feb. 1978.

[19] L.E. Dickens, "Spreading Resistance as a Function of Frequency," IEEE Trans. Microwave Theory Tech., Vol. MTT-15, No. 2, pp. 101-109, 1967.

[20] K.S. Champlin and G. Eisenstein, "Cutoff Frequency of Submillimeter Schottky-Barrier Diodes," IEEE Trans. Microwave Theory Tech., Vol. MTT-26, No. 1, pp. 31-34, 1978.

[21] U.V. Bhapkar and T.W. Crowe, "Analysis of the High Frequency Series Impedance of GaAs Schottky Diodes by a Finite Difference Technique," In press, IEEE Trans. Microwave Theory and Tech., 1992.

[22] U.V. Bhapkar, "An Investigation of the Series Impedance of GaAs Schottky Barrier Diodes," M.S. Thesis, University of Virginia, May 1990.

[23] E. Kollberg, T. Tolmunen, M. Frerking and J. East, "Current Saturation in Submillimeter Wave Varactors," 2nd Int'l. Symp. on Space THz Technology, pp. 306-322, Pasadena, CA, Feb. 1991.

[24] P.H. Siegel and A.R. Kerr, "The Measured and Computed Performance of a 140-220 GHz Schottky Diode Mixer," IEEE Trans. Microwave Theory Tech., Vol. MTT-32, No. 12, pp. 1579-1590, Dec. 1984.

[25] W.C.B. Peatman, P.A.D. Wood, D. Porterfield, T.W. Crowe and M.J. Rooks, "A Quarter-Micron GaAs Schottky Barrier Diode with High Video Responsivity at 118 μm," submitted to the Appl. Physics Lett., Feb. 1992.
[26] J. Hernichel, F. Lewen, K. Matthes, M. Klumb, T. Rose, G. Winnewisser and P. Zimmermann, "Submillimeter Receiver Development at the University of Cologne," Proceedings, Second Intl. Symp. Space Terahertz Tech., Pasadena, CA, pp. 641-647, February 1991.
[27] P. Zimmermann, Radiometer Physics, Meckenheim, Germany, private communication, Nov. 1991.
[28] Ralph Zimmermann, Ruediger Zimmermann and Peter Zimmermann, "All Solid-State Radiometers for Environmental Studies to 700 GHz," Third Intl. Symp. Space Terahertz Tech., Ann Arbor, Mich., March 1992.
[29] A.I. Harris, D.T. Jaffe, J. Stutzki and R. Genzel, "The UCB/MPE Cassegrain Submillimeter Heterodyne Spectrometer," Int. J. IR and MM Waves, Vol. 8, No. 8, pp. 857-883, Aug. 1987.
[30] H.P. Roeser, Max Planck Institute for Radioastronomy, Bonn, Germany, private communication, Feb. 1992.

Table I : Schottky Receiver Performance from 100 GHz through 2.5 THz

Frequency (GHz)	Diode Type	Epilayer Doping (cm^{-3})	Anode Diameter (μm)	Receiver Noise Temperature (K, SSB)	Receiver Noise Temperature ((hv/k), SSB)	Reference
100	2P9	$5x10^{16}$	3.0	124	26	Predmore [15]
345	2I1-150	$5x10^{16}$	2.0	760	46	Hernichel [26]
490	1T6	$4x10^{17}$	0.5	1,000	43	Zimmermann [27]
650	1T6	$4x10^{17}$	0.5	3500	112	Zimmermann [28]
800	1E7	$2x10^{17}$	0.8	7,300	190	Harris [29]
1,400	1I12	$5x10^{17}$	0.5	14,000	209	Roeser [1]
1,400	1T15	$1x10^{18}$	0.25	10,000	149	Roeser† [30]
2,500	1I12	$5x10^{17}$	0.5	25,000	208	Roeser [1]

† A preliminary result, this diode has not yet been tested at 2.5 THz.

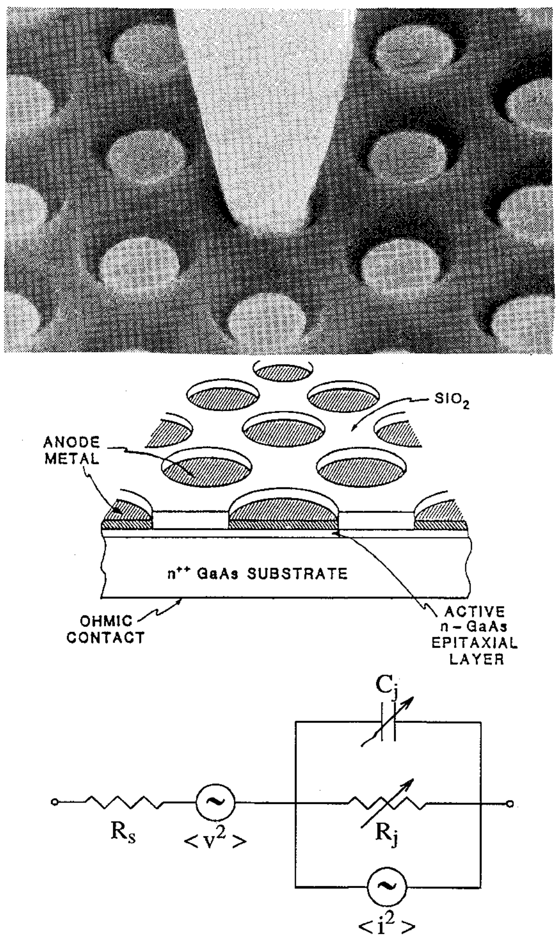

Fig. 1. A scanning electron micrograph of a whisker contacted Schottky diode chip (top), a schematic drawing of a diode chip (middle), and an equivalent circuit (bottom).

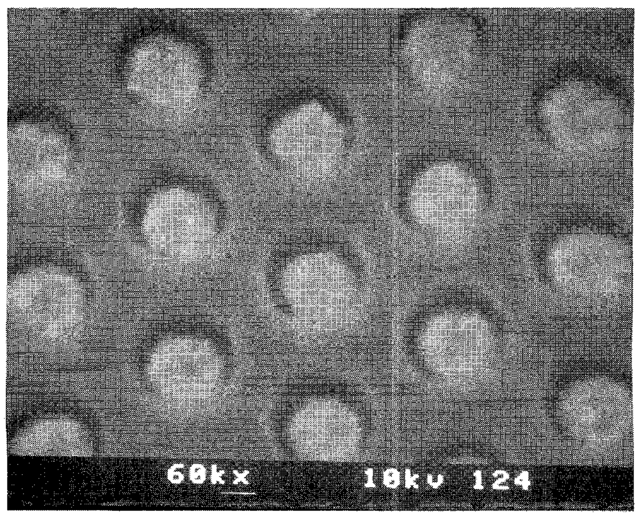

Fig. 2. A scanning electron micrograph of a diode chip with quarter-micron anode diameters. The center-to-center spacing is 0.5 microns.